An integrated GIS-based model to evaluate the tsunami vulnerability of building using fragility function and tsunami simulation

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1. Introduction

Tsunami fragility function is defined as the structural damage probability of buildings against hydrodynamic features of tsunami inundation flow i.e. velocity, hydrodynamic force, inundation depth (Koshimura et al., 2009). Tsunami fragility functions have been developed in response of some of the biggest tsunami events around the world. For instance, in Phang Nga, Thailand after the 2004 Indian Ocean tsunami (Suppasri et al., 2011), in Dichato, Chile after the 2010 Chilean Tsunami (Mas et al., 2012), and most recently after the 2011 Tohoku Earthquake Tsunami (Suppasri et al., 2012). Consequently, based on architecture and engineering characteristics of buildings in these countries, there are several fragility functions that can be used for structural vulnerability assessment in coastal communities. Initial applications of tsunami fragility function to evaluate the structural vulnerability of buildings against tsunami impact were introduced in Adriano et al. (2012, 2013). In this study, we integrated tsunami fragility function and tsunami simulation into a GIS-based model in order to investigate the building vulnerability.

2. Methodology

Tsunami fragility function was introduced as a new measure for the estimation of tsunami damage to buildings and basically is a macroscopic representation of the structural damage probability. For example, considering that there are 100 building exposed to 4 m inundation depth. Based on the fragility function shown in Fig. 1a, the probability of damage at 4 m inundation depth is 80%. Consequently, 80 buildings from 100 exposed buildings may be damaged. However, this application presents two main uncertainties, i) the unknown timing of damage, and ii) the unknown geospatial location of the damaged buildings.

2.1. Temporal application of fragility function

Focusing on the statistical approach and following basic probability theory, a curve derived similarly to the fragility functions can also represent the probability of damage of one single building provided the assumption of all buildings being the same i.e. material, structural type. Considering the above example (80 damaged buildings from 100 exposed buildings), and the fragility function in Fig. 1a. The probability of one single building being damaged is given in Eq. 1.

$$P(x_1|_{h=4m}) = n/N = 0.80 \tag{1}$$

where x_1 is the first building being damaged, N is the number of exposed buildings, and n is the number of damaged

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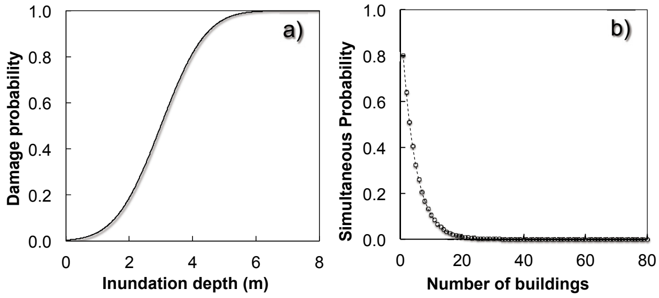

Figure 1: a) Tsunami fragility function with regard to inundation depth (Koshimura et al., 2009). b) Simultaneous probability damage curve developed from the fragility function presented in (a).

buildings. Next, in the same sample and at the same experiment ($h = 4m$), after the first building (x_1) is already damaged the total number of buildings (N) has being reduced, and then the number of damaged buildings (n) in sample also was reduced. As a result, the probability of the second building (x_2) is lower than the first (x_1). Eq. 2 gives the probability of the second building being damaged.

$$P(x_2|^{x_1}_{h=4m}) = (n-1)/(N-1) = 0.798 \tag{2}$$

If in the same experiment ($h = 4m$) we would like the two events to occur at the same time, the conditional probability is used as an estimation of one event happening when knowing that the other occurs or have occurred. The probability of x_1 and x_2 being simultaneously damaged is given in Eq. 3.

$$P(x_1 x_2) = P(x_1|_{h=4m}).P(x_2|^{x_1}_{h=4m}) = 0.638 \tag{3}$$

Then, the probability of i buildings being simultaneously damaged is given in Eq 4. Following this concept the curve shown in Fig. 1b (for $h = 4m$ and $n = 100$) can be developed.

$$P(x_1 x_2 ... x_i) = P(x_1|_{h=4m}).P(x_2|^{x_1}_{h=4m})...P(x_2|^{x_1,x_2...x_{i-1}}_{h=4m}) \tag{4}$$

Finally, the multiplication of n and $P(x_1 x_2 ... x_i)$ gives the number of buildings being simultaneously damaged.

2.2. Spatial application of fragility function

The spatial location of the total number of buildings being simultaneously damaged at a representative inundation depth, on each time step of numerical simulation, is determined according to its geospatial locations into inundated area, which is calculated at the current time step.

$$Combination = 0.50 \times M + 0.25 \times D + 0.25 \times V \tag{5}$$

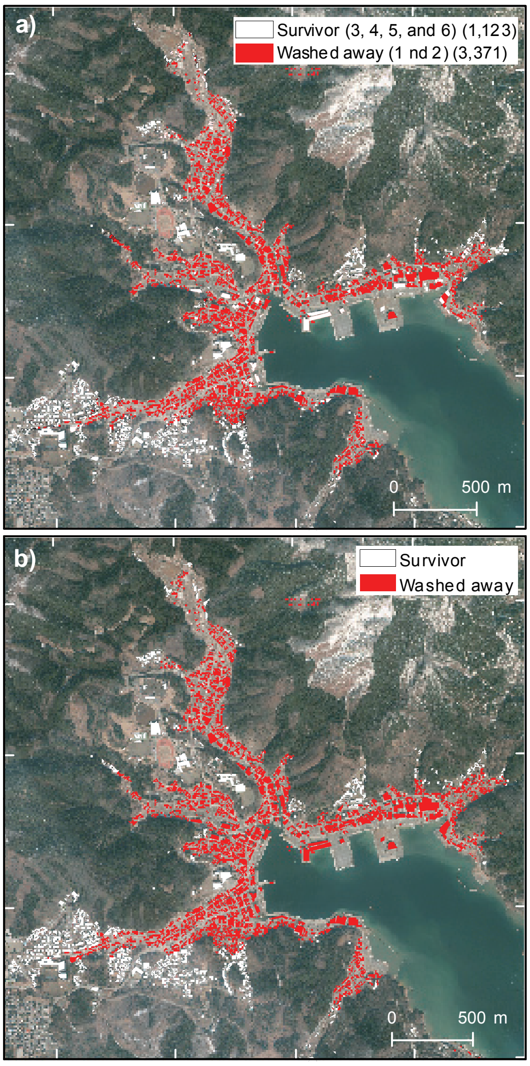

Figure 2: Comparison between the MLIT's GTD and the GIS-based model result. a) Re-classified damage level of MLIT data. b) GIS-based model results.

The final geospatial-selection is based on the weighted combination (see Eq. 5) of each building's construction material (M), exposed inundation depth (D), and exposed flow velocity (V).

3. Application and Results

To apply the GIS-based model, we focus on Onagawa town of northeast Tohoku region. The tsunami attacked this town at 15:20 (35 minutes after the earthquake occurred) with areas where the maximum run-up height exceeded 30 m, causing 816 fatalities and 125 still missing (Mori et al., 2012; Koshimura et al., 2013). We use the 2011 Tohoku Earthquake's source model developed by Satake et al. (2013). The inundation numerical simulation is calculated using 5 m grid size. In order to validate the GIS-base model result, the seven different damage levels of buildings due to the 2011 Tohoku Earthquake Tsunami published by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) was re-classified into two levels (see Fig. 2a) and employed as ground truth data (GTD).

Based on the simulation condition, the GIS-based model shows that approximately 42 minutes after the earthquake occurred, there were about 2400 building within the inundation area that were exposed to the tsunami inundation features. However, according to our results, about 500 buildings might be damaged at that moment. This time (42 minutes) shows the maximum number of damaged buildings with 3 hours of numerical simulation.

The preliminary results have shown that our model slightly overestimates the number of washed away building. The result, however, presents an overall accuracy of 89.3%. This initial result was calculated considering that our model performs the geospatial-selection, at each computational time step, based on three parameters (contraction material, inundation depth, and flow velocity). Therefore, the selection of the damaged building on each step can be improved by including other parameter such as number of stories and hydrodynamic force.

4. Conclusions

We introduced and GIS-based method to investigate the tsunami damage vulnerability using numerical simulation and tsunami fragility function. The tsunami inundation modelling was performed using the 2011 Tohoku Earthquake as source scenario. This model was tested in Onagawa town. The comparison between our model results and MLIT's GTD showed an overall accuracy of 89.3%. The GIS-based model may help local authorities better understand the tsunami building vulnerability and address preventive actions.

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